

# Proposal to Investigate Silicon CMOS

Whitney Armstrong  
David Blyth  
Jessica Metcalfe (PI)  
José Repond (co-PI)  
Junqi Xie

*Argonne National Laboratory*

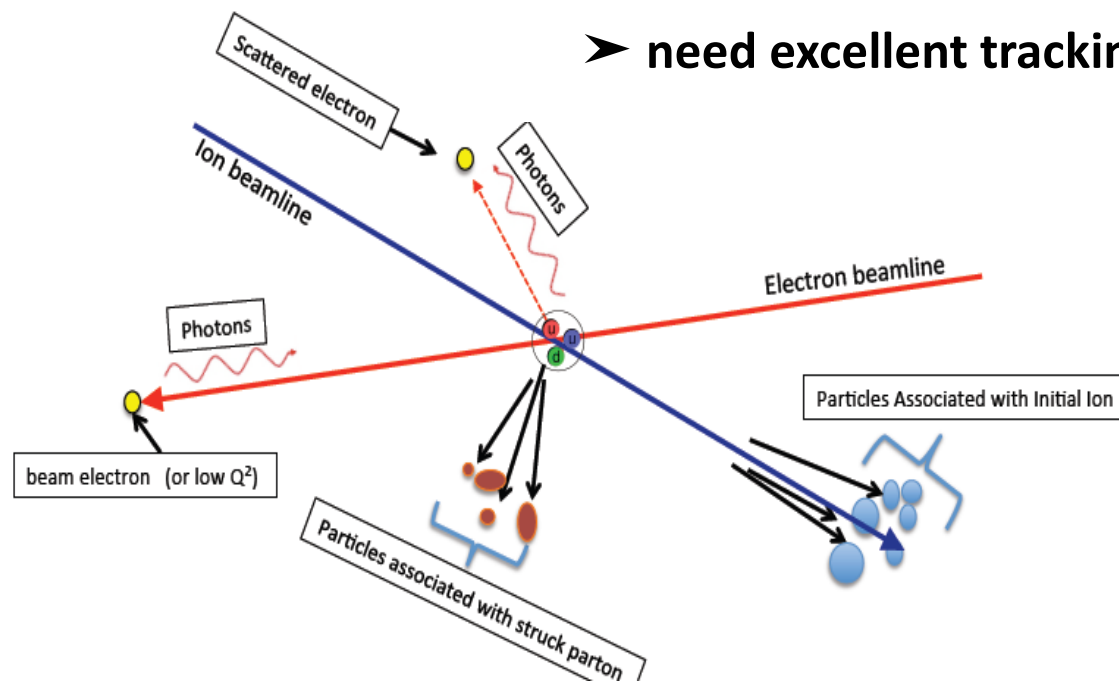
## Physics Goals of the EIC:

- Understand the nature of the gluon structure
- Measure nucleon and nuclear structure
  - includes transverse and flavor structure

## To Achieve the Physics Goals of the EIC:

- Measure the transverse momentum dependent parton distributions (TMDs)
- Measure the heavy flavor production in deep inelastic scattering and the related charm and beauty parton distributions

➤ need excellent tracking, particle ID

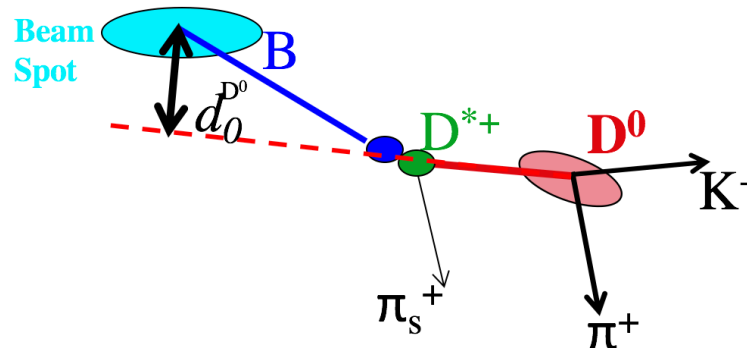
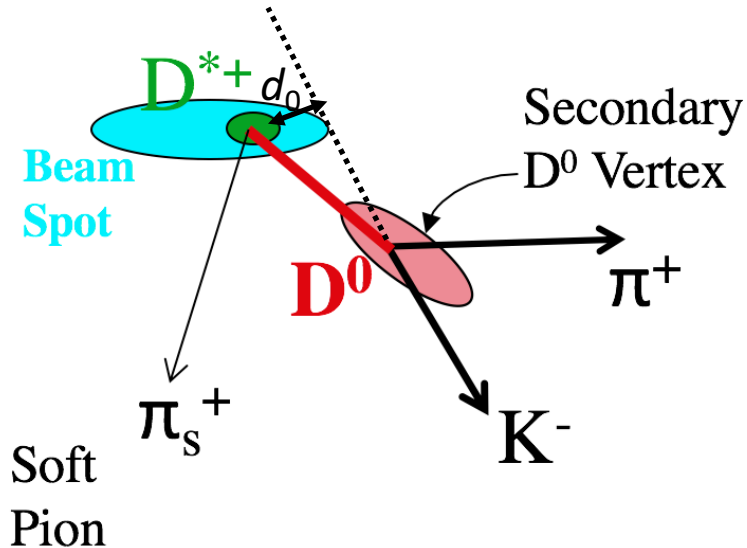


## Tracking Requirements:

- Secondary vertex reconstruction
- Impact Parameter Resolution,  $d_0$
- Small pixels for high position resolution
- Low mass budget to avoid secondary interactions

particle	$c\tau$
$\pi^\pm$	7.8 m
$\pi^0$	25 nm
$K^\pm$	3.7 m
K0S	2.7 cm
K0L	15.3 m
$D^\pm$	312 $\mu\text{m}$
$D^0$	123 $\mu\text{m}$

Particles resulting from the struck parton:



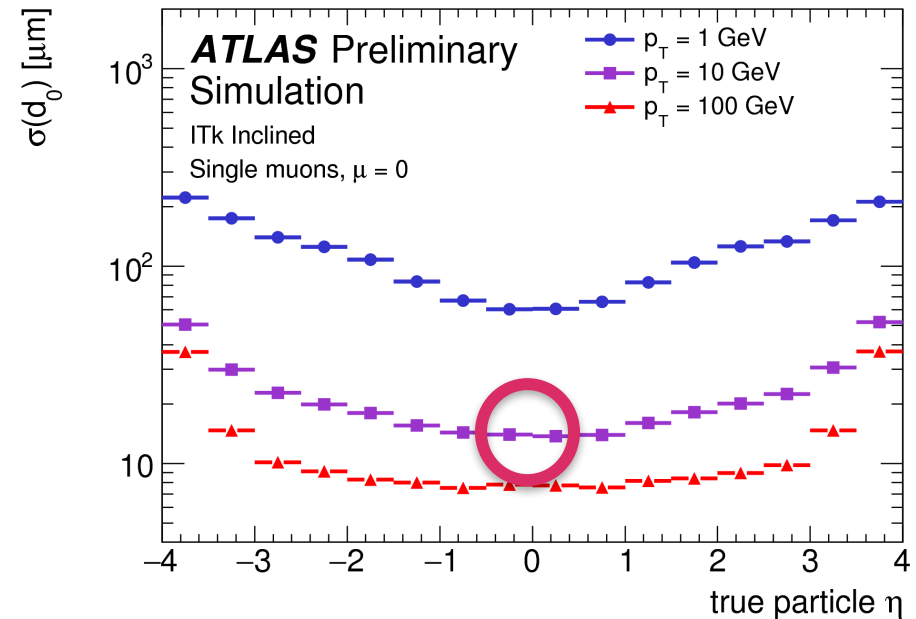
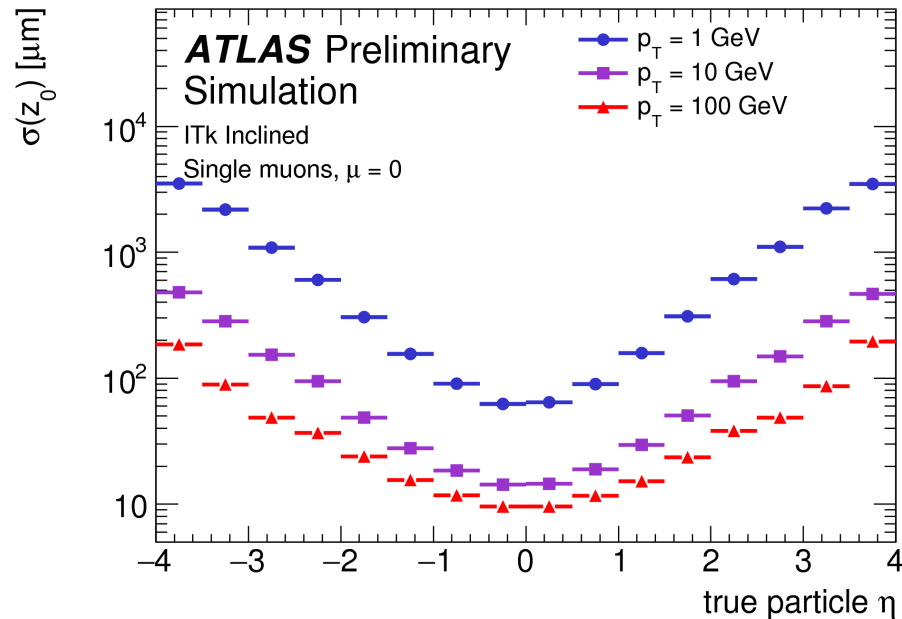
# Example Performance

Example:

ATLAS ITK Upgrade with  $50\ \mu\text{m} \times 50\ \mu\text{m}$  pixels

- Includes high pileup -> not a factor at the EIC
- Expect further improvement

ATL-PHYS-PUB-2016-025

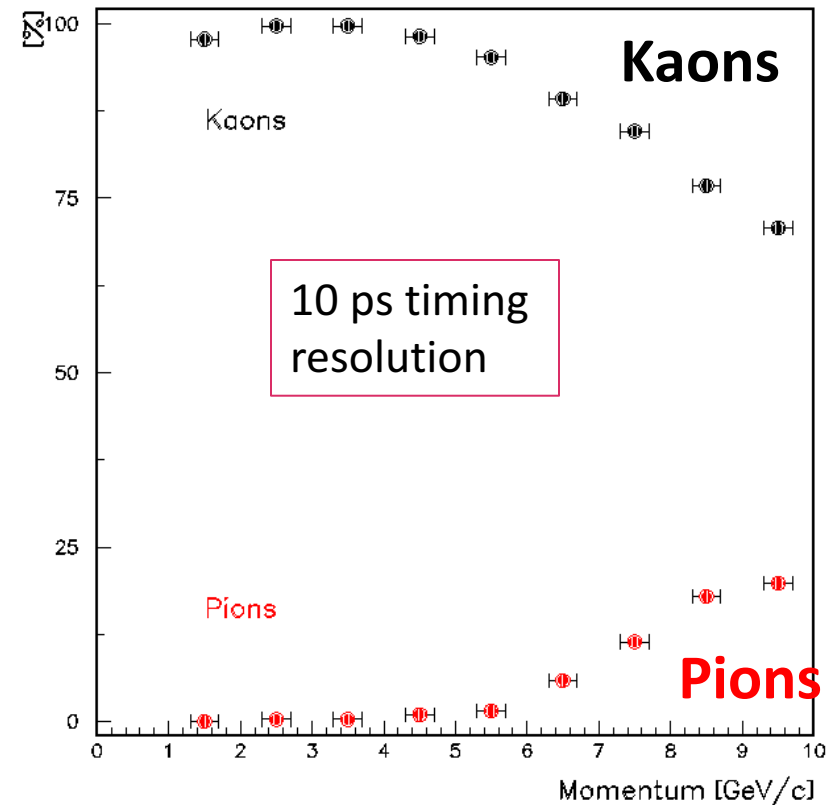
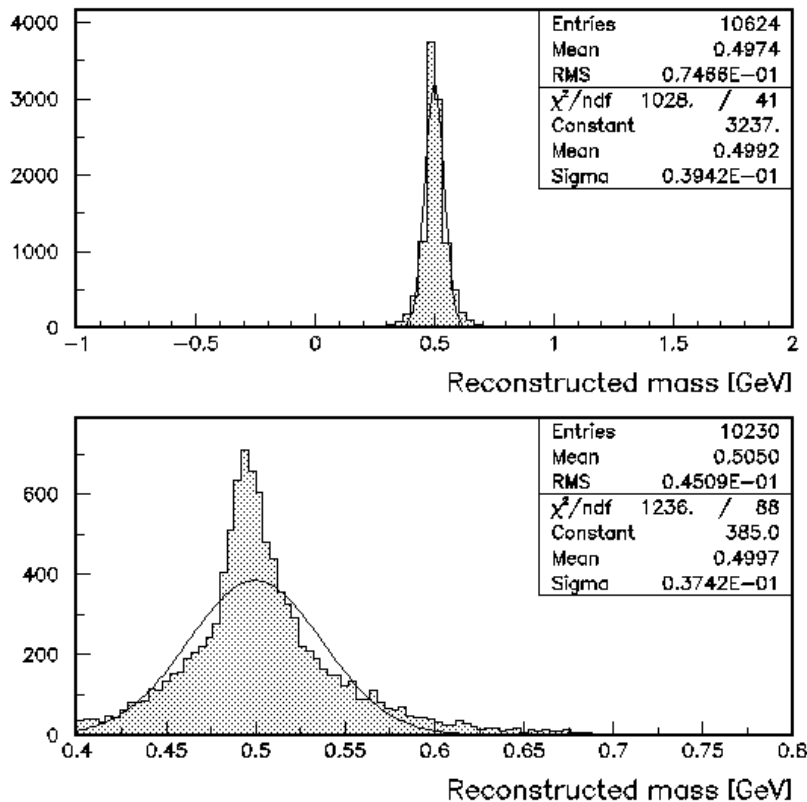


- Excellent impact parameter performance
- $d_0 < 30\ \mu\text{m}$  for  $|\eta| < 3.5$ ,  $< 50\ \mu\text{m}$  for  $|\eta| < 4$  for  $p_T = 10\ \text{GeV}$  muons
- $z_0 < 300\ \mu\text{m}$  for  $|\eta| < 3.5$ ,  $< 450\ \mu\text{m}$  for  $|\eta| < 4$  for  $p_T = 10\ \text{GeV}$  muons

## Time of Flight for Particle ID

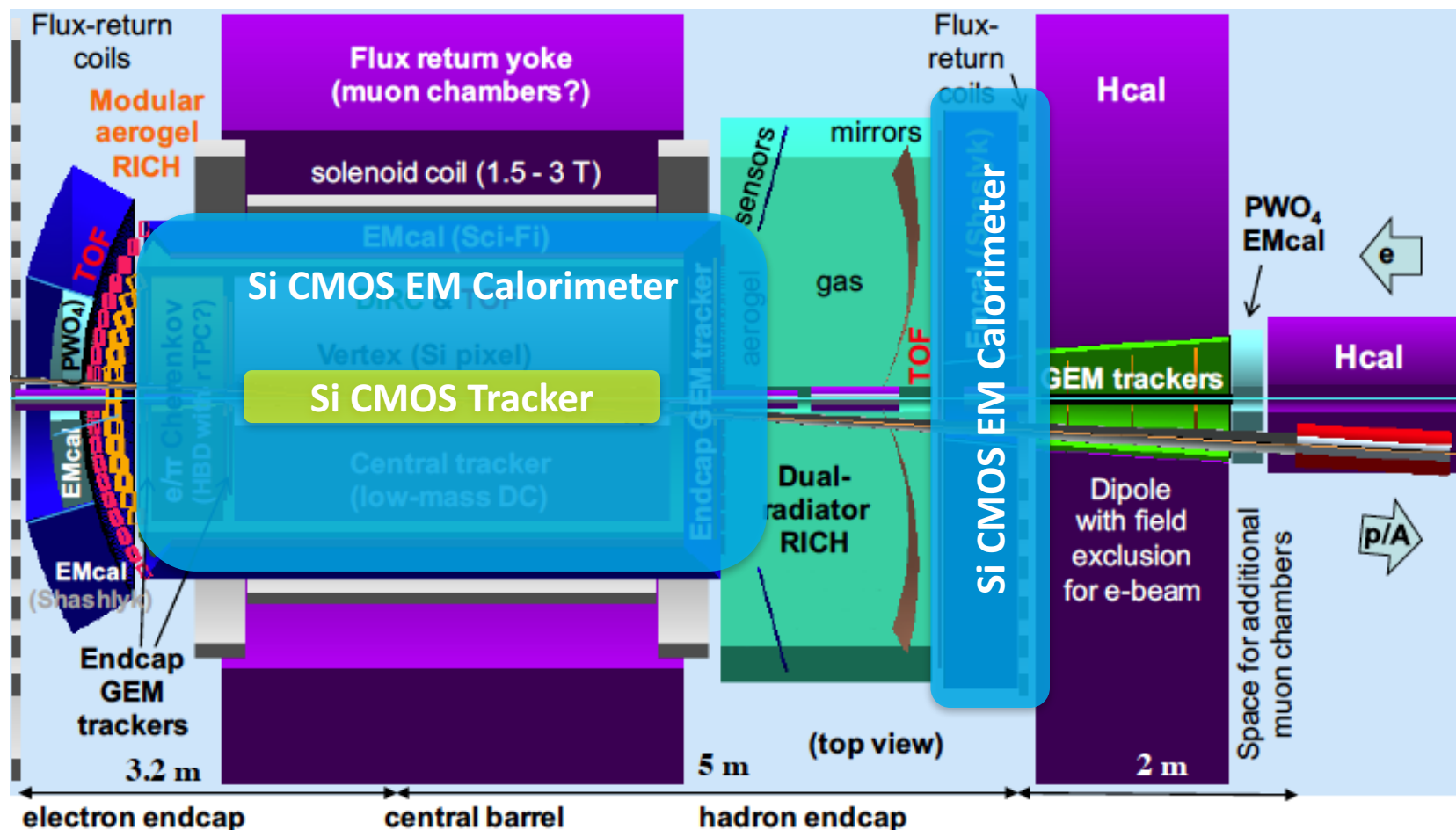
Preliminary Results from Argonne EIC Simulation Group:

- Time information associated with each particle in the silicon tracker and EM calorimeter using a single particle gun and an SiD detector
- Timing resolution of **10 ps** allows for excellent kaon-pion separation



# Example EIC Detectors

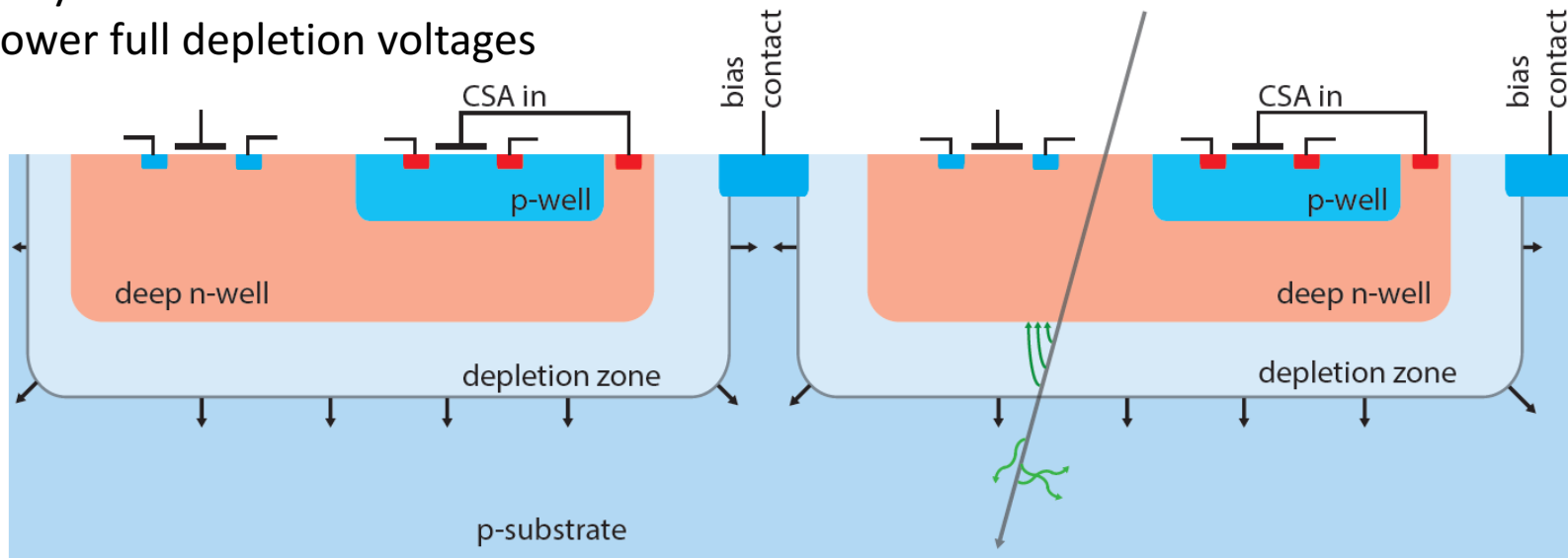
A proposed JLab Detector for the EIC:



Propose to investigate monolithic CMOS technologies that can provide necessary position resolution (Tracker) and particle ID (EM Calorimeter, Forward EM Calorimeter)

## Monolithic HVCMOS

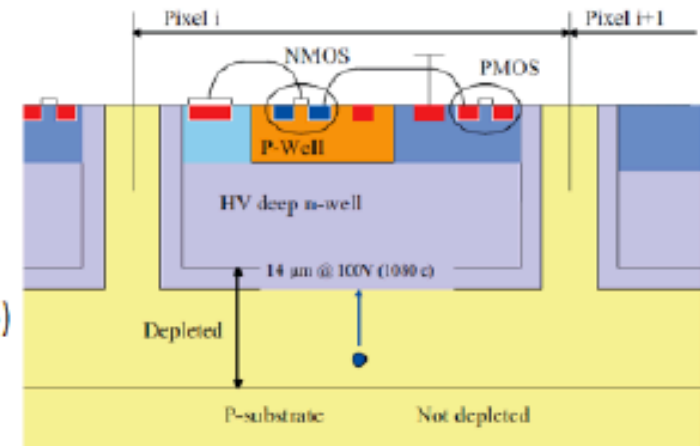
- Under consideration for the ATLAS Phase II pixel detector upgrade
- Less expensive by x2 than traditional silicon sensors
- Integrated sensor + signal amplification
- Use commercially available CMOS processing with a few modifications
  - Deep n-well to isolate on-pixel electronics
  - high resistivity substrates for high voltage without breakdown
- Timing is currently  $\sim 1\text{-}100\text{ ns}$ 
  - collect by drift, not diffusion
- pixel sizes down to at least  $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$
- fully monolithic reduces material
- lower full depletion voltages



## ams 0.35 $\mu\text{m}$ /180 nm

### Key features:

- **Technology node** 0.35  $\mu\text{m}$ /180 nm
- **Wells** No possibility of isolating n-wells from the collecting deep n-well. No CMOS electronics in the sensor area. Can induce cross-talk.
- **Metal layers** 4/6
- **HR** 20 (standard value) – 1k  $\Omega\cdot\text{cm}$  (since 2015/6)
- **HV** -150 V < HV < 0 V
- **Depletion region** 140  $\mu\text{m}$  thick
- **Backside biasing** Not possible
- **Stitching** Not possible

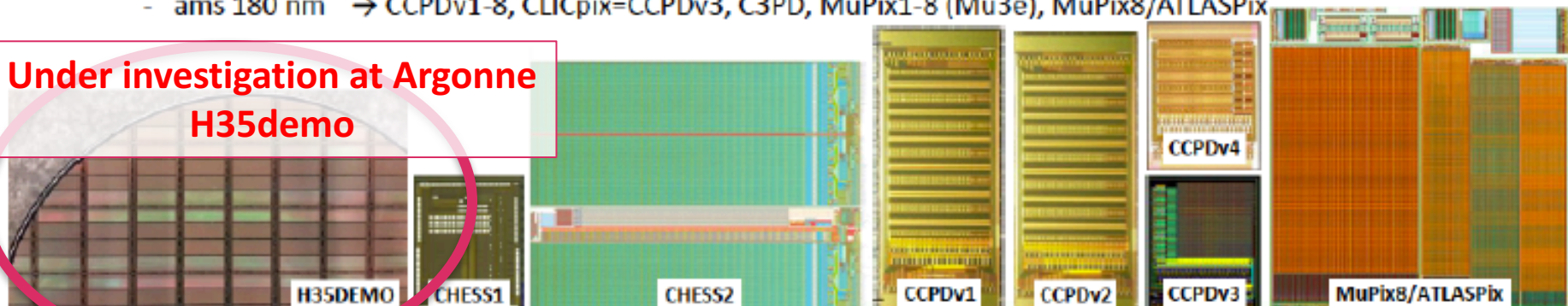


*I. Peric, NIMA 650 pp. 158-162, 2011*

### Prototypes:

- ams 0.35  $\mu\text{m}$  → Initial R&D developments, H35CCPDv1-2, H35DEMO, HVStrip, CHESS1-2 (strips)
- ams 180 nm → CCPDv1-8, CLICpix=CCPDv3, C3PD, MuPix1-8 (Mu3e), MuPix8/ATLASPix

Under investigation at Argonne  
H35demo





## HVCMOS sensor

- Monolithic matrices
- Capacitively coupled to FEI4 (glued)

## Resistivities:

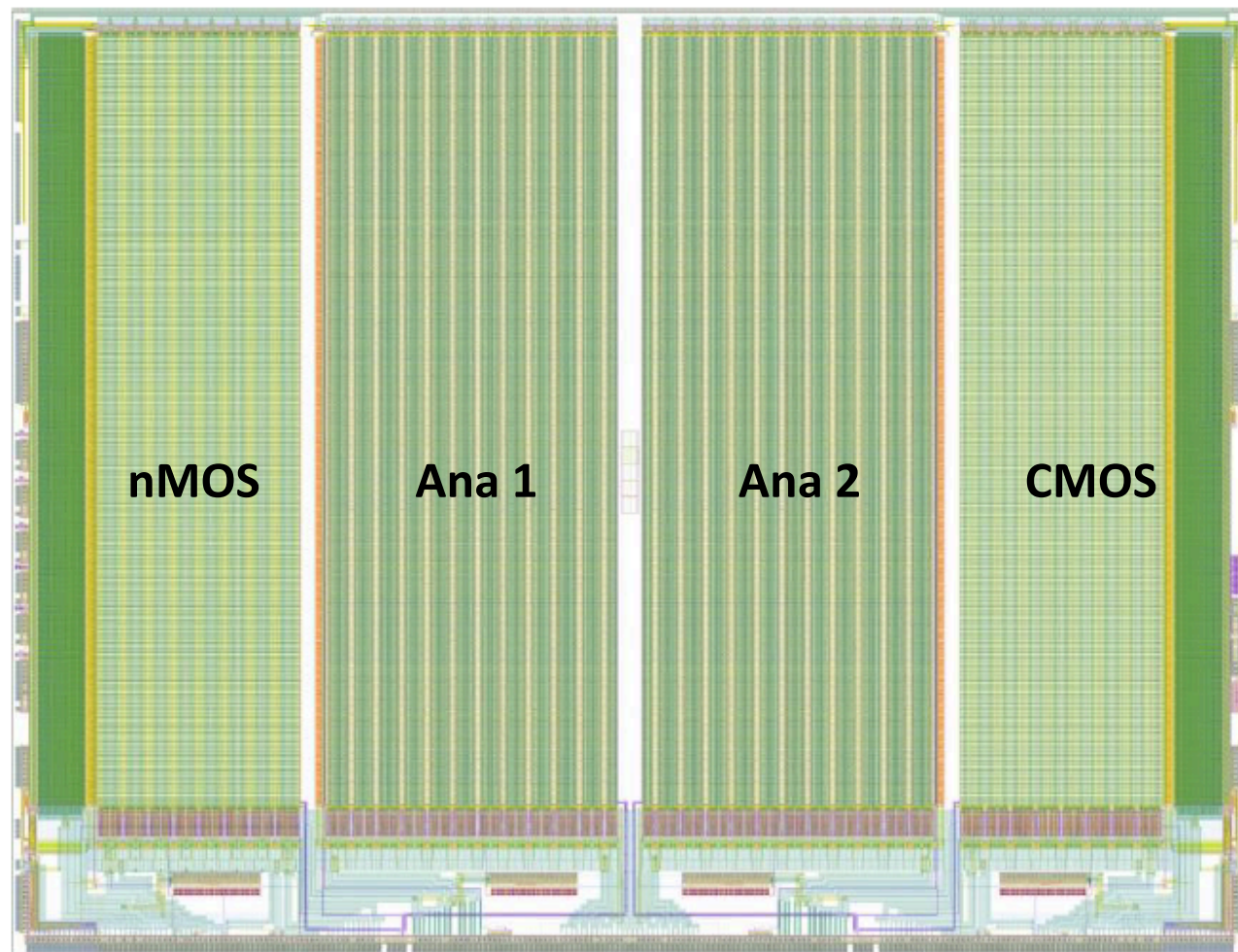
- 20  $\Omega$
- 80  $\Omega$
- 200  $\Omega$
- 1000  $\Omega$

## Thickness:

- 300  $\mu\text{m}$
- 100  $\mu\text{m}$

## Bias Voltage

- Top side
- Back side (separate process from AMS)



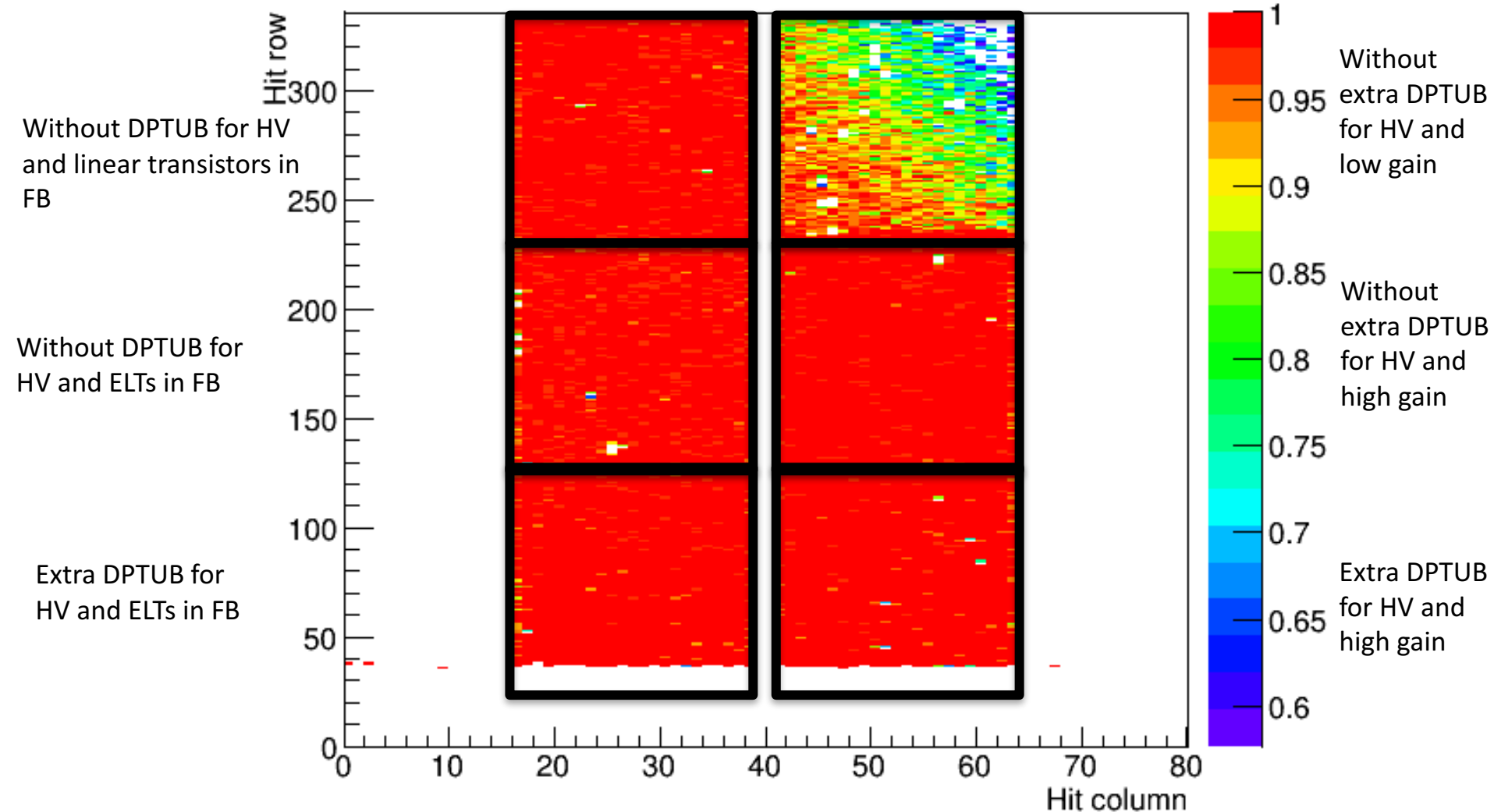
## Preliminary Results

- Non-optimized track matching

## Tracking Efficiency

Ana 1

Ana 2



## Proposal:

- Characterization measurements of CMOS pixel structures relevant to the EIC
  - Timing
  - thinned sensors
  - Back-side bias voltage
  - Optimized designs (comparators, amplifiers, high gain, etc.)
  - H35demo, H18 (MuPix8/ATLASPix)
- Include pixel geometries relevant to the EIC in the next design submissions
  - Rely on input from Argonne EIC simulations group
- Leverage ongoing work in Argonne HEP in this area

## Toward 10 ps Timing Resolution:

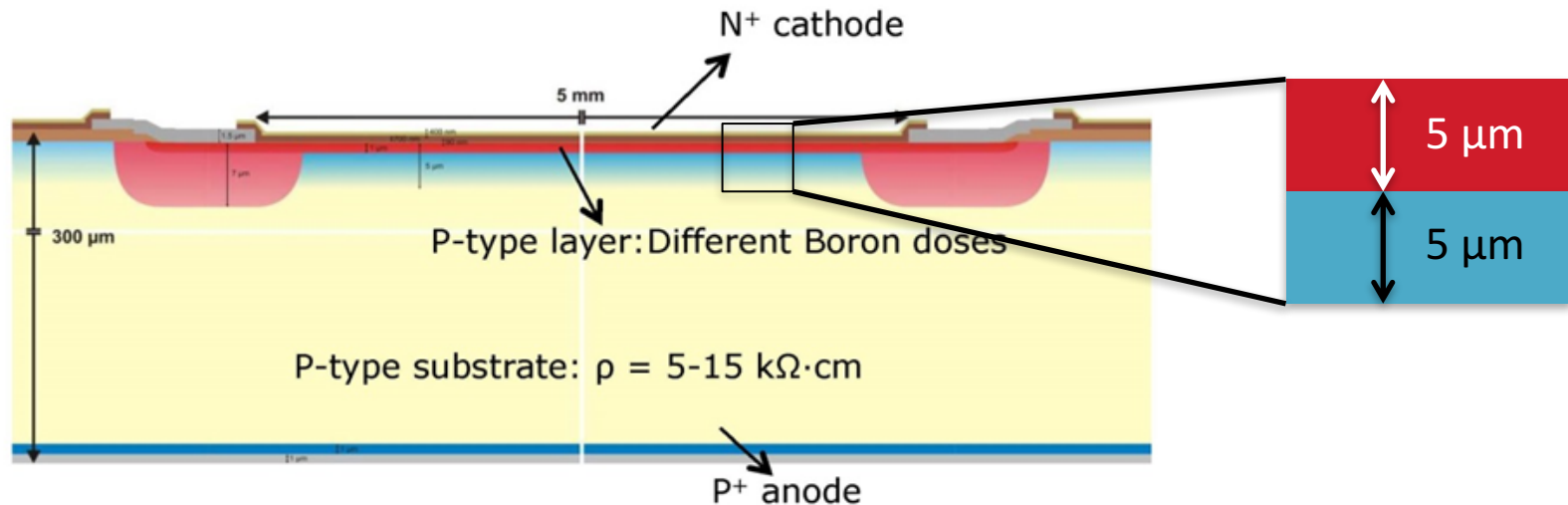
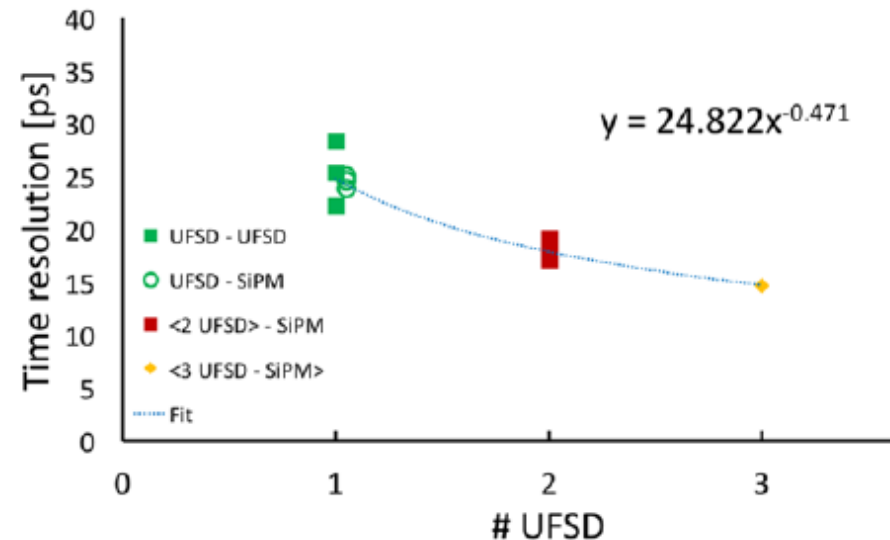
- Work with CMOS designer, Ivan Peric, to develop a design
  - CMOS plus a gain layer similar to that in an LGAD silicon sensor
  - Use TCAD simulation to demonstrate potential
  - Determine how these technologies would benefit an EIC detector

# Low Gain Amplifying Detectors (LGAD)

## LGAD

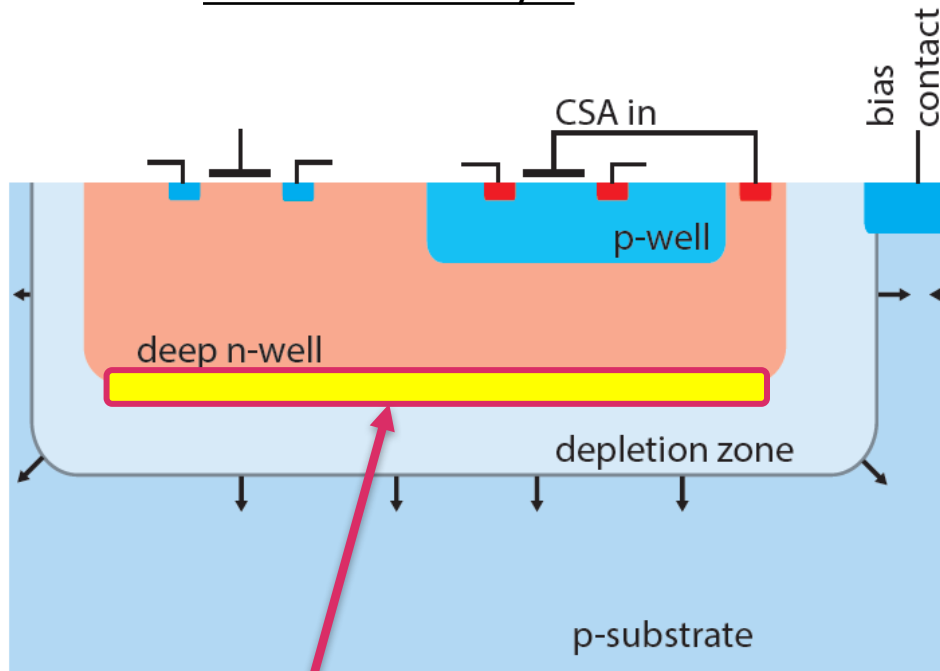
- amplification region,  $\sim 5 \mu\text{m}$  thick
  - thin layer of Boron or Gallium
  - modifies the effective doping concentration profile  $\rightarrow$  electric field profile to create high field gradient
- Radiation tolerance shown up to  $10^{14} n_{\text{eq}}/\text{cm}^2$ 
  - not as tolerant as traditional silicon due to the high reactivity of the accelerant layer

UFSD beam test: V Bias = 240V



Discussions with Ivan Peric (AMS CMOS designer):

## CMOS + Gain Layer



Gain layer  
similar to LGAD  
design

- Possible foundries:
  - AMS, Lfoundry
- May be possible to include a gain layer in the next AMS MPW run
- Need to add to the TCAD simulations
  - Understand constraints on pixel size

- 1) The postdoc will carry out test bench measurements in the lab at Argonne as well as test beam measurements at Fermilab and/or CERN. These include:
  - Characterization of design options for an EIC
  - Precision timing measurements of charge collection properties
  - Test beam performance measurements with particle species and energies specific to the EIC
- 2) The postdoc will also perform TCAD simulations using an existing license at Argonne.
  - TCAD simulations of existing samples will be set up at Argonne
  - TCAD simulation results will be compared to measurements
  - An iterative process will aim at identifying the underlying cause of any discrepancies and the simulation will be corrected
- 3) The postdoc will work with our collaborating design engineers to identify modifications in simulation toward a design optimized for timing precision at the EIC.

Budget Scenarios	Postdoc Salary (\$k)	Design Engineer (\$k)	Travel (\$k)	Total Cost (\$k)
Nominal	\$125	\$30	\$0	\$155
-20%	\$125	\$0	\$0	\$125
-40%	\$93	\$0	\$0	\$93

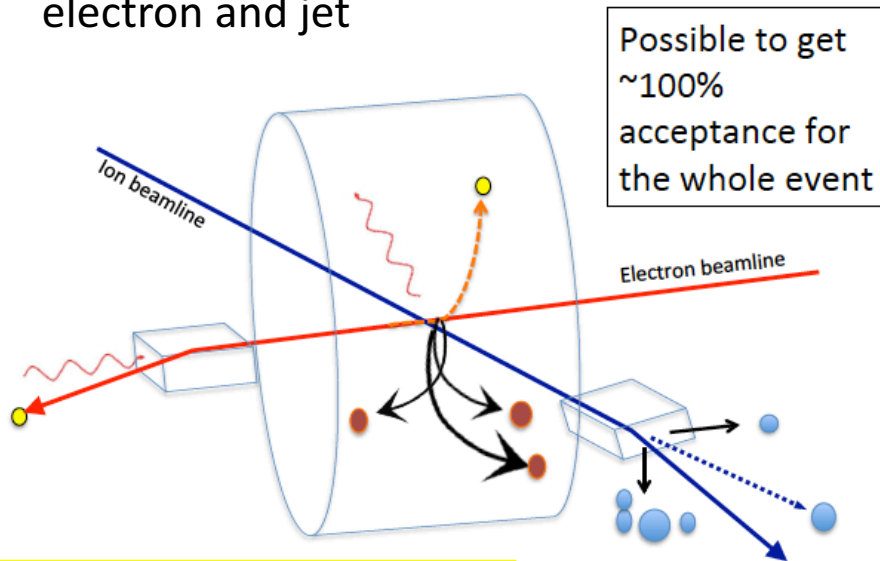
- The nominal budget will complete all three deliverables in the first year.
- The nominal budget minus 20% will complete deliverable items 1-2 since the third item requires compensation for a design engineer and this funding would be dropped first.
- The nominal budget minus 40% will complete only the first deliverable using 0.75 FTE of the postdoc the other 0.25 FTE would be funded for different work under the EIC LDRD program.

## Thank You

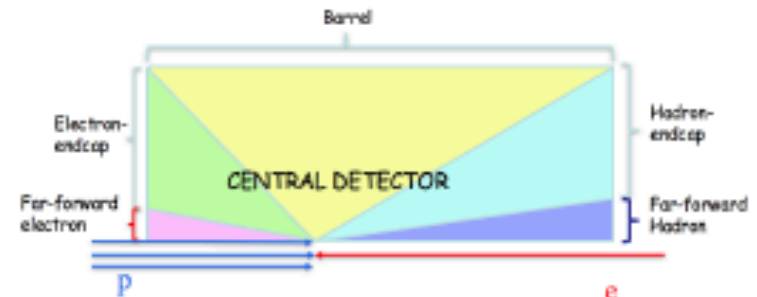
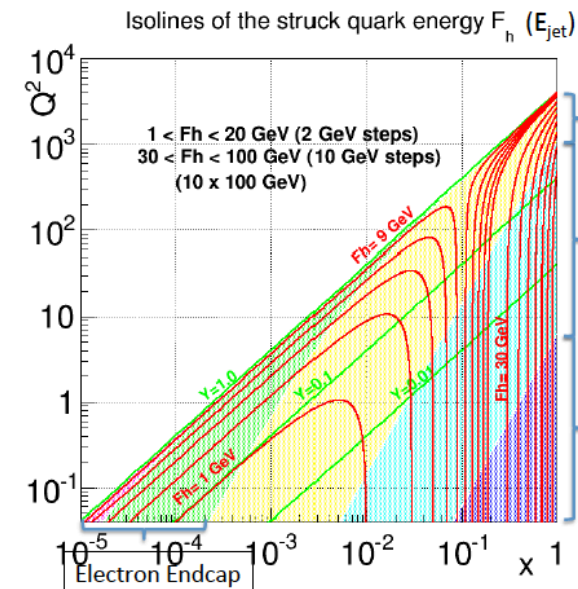


## Measure $x$ and $Q^2$

- $x$ : measure of the momentum fraction of the struck quark in a proton
- $Q^2$ : measure of the resolution
- via energy and angle of scattered electron and jet



Total acceptance detector (and IR)

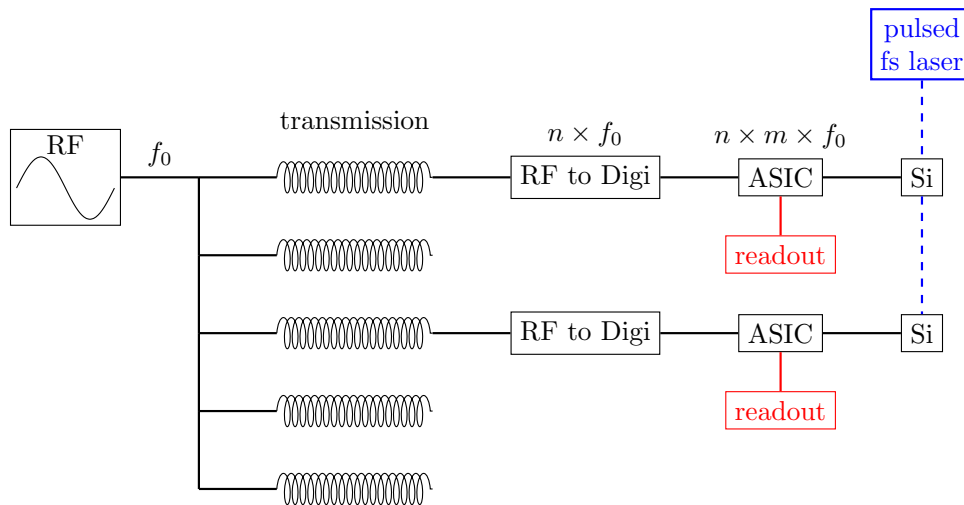


Rik Yoshida EIC Detector R&D meeting July 2016

➤ need excellent tracking, particle ID

Separate Argonne Effort on Detector-Wide Timing Synchronization:

- Goal is to maintain the integrity of the clock between detectors
- requires maintaining low phase noise/jitter from a single reference signal
- Strategy is to use an RF clock



## Luminosity

- up to  $10^{34}$
- expect  $<0.1$  interactions per event
  - Pileup should not be an issue, still need to identify primary vertex
- Bunch crossing  $\sim 10$  ns
  - Fast readout or time stamp to identify bunch crossing for an event

## Vertexing

- Hadron beam spot  $\beta = 5$  cm
- Low material budget

## Particle identification

- time of flight
- $dE/dx$

## Radiation damage

- $< 1 \times 10^{10}$  1 MeV  $n_{eq}/cm^2$ 
  - Not an issue for most silicon technologies

## Material Budget

- Keep as low as possible

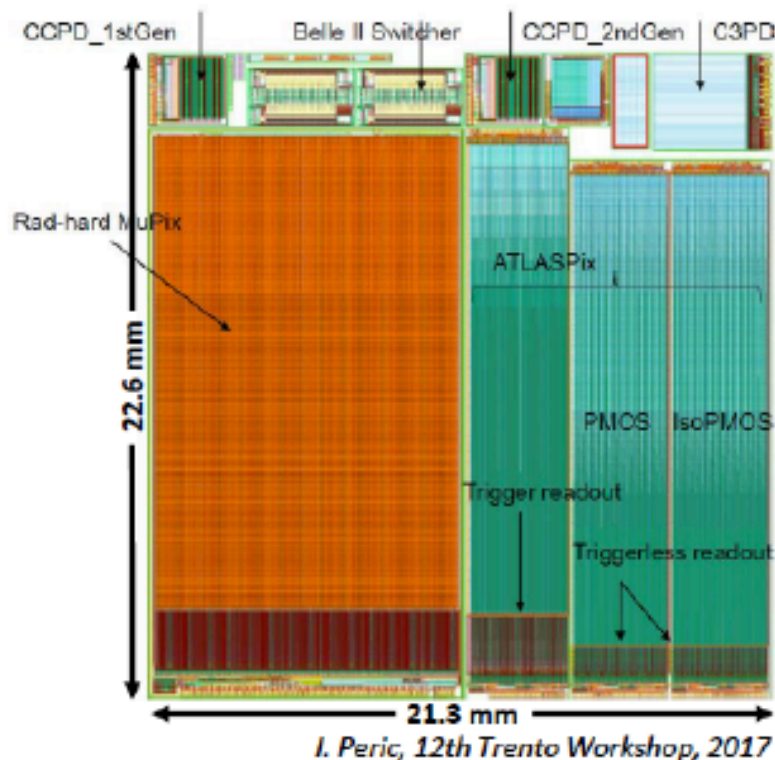
## ams 180 nm – MuPix8/ATLASPix and new design

### MuPix8/ATLASPix:

- Submitted in January 2017 (eng. run)
- It includes:
  - Matrices of pixels for ATLAS
    - Pixel size:  $25\ \mu\text{m} \times 25\ \mu\text{m}$ ,  $25\ \mu\text{m} \times 50\ \mu\text{m}$ ,  $33\ \mu\text{m} \times 125\ \mu\text{m}$ ,  
 $50\ \mu\text{m} \times 60\ \mu\text{m}$ ,  $40\ \mu\text{m} \times 125\ \mu\text{m}$
  - MuPix8
    - Pixel size:  $80\ \mu\text{m} \times 81\ \mu\text{m}$
    - Matrix with  $200 \times 128$  pixels
    - Pixels with CSA and output driver only
    - Hit info: x-address, y-address, 10-bit TS, 6-bit amplitude
    - Time resolution: 6.25 ns
    - Nominal power consumption: 300 mW per matrix
- Hit driven, triggerless R/O (MuPix8, Simple ATLASPix)
- Triggered R/O (M ATLASPix)
- Resistivity:  $20\ \Omega\cdot\text{cm}$ ,  $50\text{-}100\ \Omega\cdot\text{cm}$ ,  $100\text{-}400\ \Omega\cdot\text{cm}$ ,  
 $600\text{-}1.1\text{k}\ \Omega\cdot\text{cm}$

### New design:

- Studies considering the integration of RD53-like periphery logic

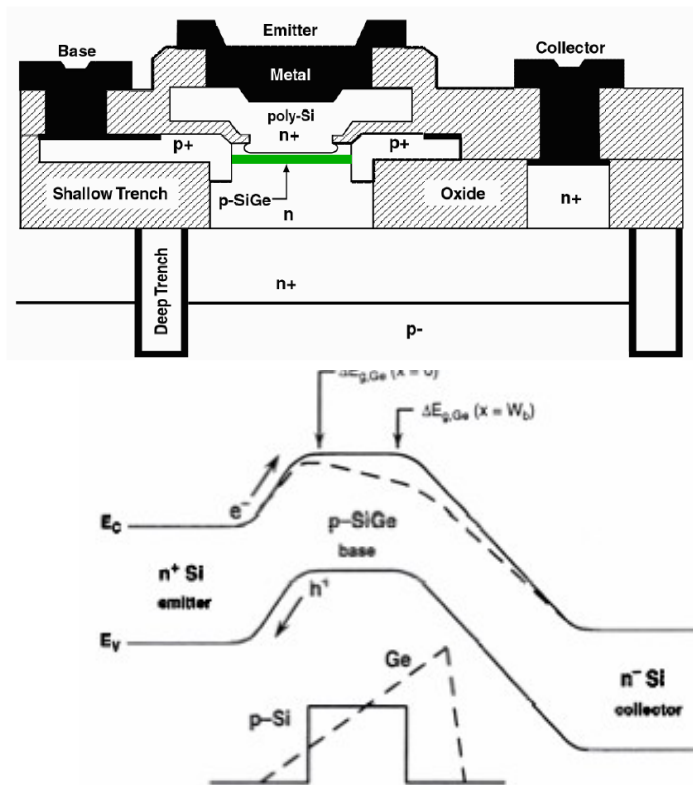


## Advantages of SiGe Bipolar Over CMOS for Silicon Strip Detectors

- A key element in the design of low noise, fast shaping, charge amplifiers is high transconductance in the first stage.
- With CMOS technologies, this requires relatively larger bias currents than with bipolar technologies.
- The changes that make SiGe Bipolar technology operate at 100 GHz for the wireless industry coincide with the features that enhance performance in high energy particle physics applications.
  - Small feature size increases radiation tolerance.
  - Extremely small base resistance (of order 10-100  $\Omega$ ) affords low noise designs at very low bias currents.
- These design features are important for applications with:
  - Large capacitive loads (e.g. 5-15 pF silicon strip detectors)
  - Fast shaping times (e.g. accelerator experiments with beam crossing times of tens of nanoseconds in order to identify individual beam crossing events)

## Second Option:

- Monolithic (CMOS-like) design based in SiGe HBT technology
  - Faster than CMOS due to band-gap engineering



TT PET results presented at TIPP 2017:

Time Difference Detector 1 - 2, MIP, bias 2.3V/ $\mu$ m

